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Characteristics of Specialised Firefighter Clothing Used in Poland – the Thermal Parameters

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Abstract

This paper describes the characteristic thermal parameters of firefighters' personal protective clothing (FFPPC) used in Poland. The total thermal insulation and evaporative resistance of three different types of FFPPC were measured and used on a thermal manikin. Next, the results were compared. Based on the analyses and calculations of the test results, it was shown that FFPPC provides a barrier to the heat exchange between the user and the surrounding environment. Differences in the local thermal insulation can be triggered not only by the material used but they can also be attributable to clothes fitted on the manikin. The biggest differences can be noted on the segments forming part of the manikin's trunk. No difference was found in the evaporative resistance between the clothes tested. In order to examine further the impact of the materials used on thermal parameters of protective clothing, it is necessary to carry out an analysis of the impact of individual layers.

Key words: *firefighter, special clothes, thermal manikin, thermal parameters.*

Introduction

Work in a fire environment under unnatural conditions and the specificity of firefighters working in open spaces, regardless of weather conditions, require appropriate protective clothing [1]. Firefighters' personal protective clothing (FFPPC) is used at various stages of rescue operations. It is designed to ensure protection against a number of factors, e.g. damp, low and high temperatures, flame (at a basic level), the effects of hazardous chemicals, biological contamination and mechanical injury [1].

FFPPC must meet the requirements of numerous standards (ASTM, European Standard etc.) [1] alongside a number of others, such as: thermal comfort, steam-permeability, resistance to mechanical damage, and visibility, especially in difficult weather conditions. In addition, such clothing should not impede firefighters' movements nor prevent them from effective performance in operational situations [2]. All personal protective equipment used by firefighters, including special clothing, is classified as Category III, i.e. it is subject to assessment in accredited laboratories. The result of this process is the EC type-examination certificate, which confirms compliance with the requirements of Directive 89/686/EEC, in particular the EN 469 standard [3] (according to [1, 4]).

In order to protect not only others but also themselves, firefighters must be fully concentrated on their tasks, otherwise they run a risk of making mistakes during a firefighting operation. The optimal conditions for such a type of work could be ensured by so-called thermal comfort, characterised by the thermally neutral state of the body. Comfort is influenced by two types of factors: environmental and individual. Firefighters have no influence on environmental factors i.e. they have to work in the conditions which they find on site. They can, however, influence one of the individual factors, namely their protective clothing. Inappropriate protective clothing during an operational situation can cause an increase in body temperature, leading to an increased frequency of cardiac contractions, or the increased working of sweat glands. Firefighters may be more prone to mistakes when feeling a lack of thermal comfort.

In normative documents there is no requirement regarding the value of the thermal insulation of special clothing. There is only information about the value of the evaporative resistance [3].

Main goal of research

There are many types of special clothing for firefighters, all of which satisfy the requirements of the EN 469 standard [3] but differ in terms of the materials used. This article examines the relationship between the thermal parameters of the clothing (such as the thermal insulation and evaporative resistance) and materials used.

Material and methods

Test apparatus

The study was carried out with a thermal manikin of the Newton type, manufactured by Measurement Technology Northwest (USA). It was constructed using a thermally conductive carbon-epoxy composite shell with embedded resistance wire heating and sensor wire elements. The manikin consists of 34 independently controlled segments: 1 – Face, 2 – Head, 3 – Right Upper Arm Front, 4 – Right Upper Arm Back, 5 – Left Upper Arm Front, 6 – Left Upper Arm Back, 7 – Right Forearm Front, 8 – Right Forearm Back, 9 – Left Forearm Front, 10 – Left Forearm Back, 11 – Right Hand, 12 – Left Hand, 13 – Upper Chest, 14 – Shoulders, 15 – Stomach, 16 – Middle Back, 17 – Waist, 18 – Lower Back, 19 – Right Upper Thigh Front, 20 – Right Upper Thigh Gard, 21 – Right Upper Thigh Back, 22 – Left Upper Thigh Front, 23 – Left Upper Thigh Gard, 24 – Left Upper Thigh Back, 25 – Right Lower Thigh Front, 26 – Right Lower Thigh Back, 27 – Left Lower Thigh Front, 28 – Left Lower Thigh Back, 29 – Right Calf Front, 30 – Right Calf Back, 31 – Left Calf Front, 32 – Left Calf Back, 33 – Right Foot, 34 – Left Foot (***Figure 1***). The thermal manikin allows the simulation of dry heat transfer (thermal insulation) as well as wet heat transfer (evaporative resistance) [5]. A general scheme of the division of the thermal manikin into segments is shown in ***Figure 1***.

The study was carried out in a climatic chamber (WEISS) equipped with microclimate meters (Indoor Climate Analyzer, from B&K and INNOVA) to monitor the thermal conditions during testing of the special clothing for firefighters selected.

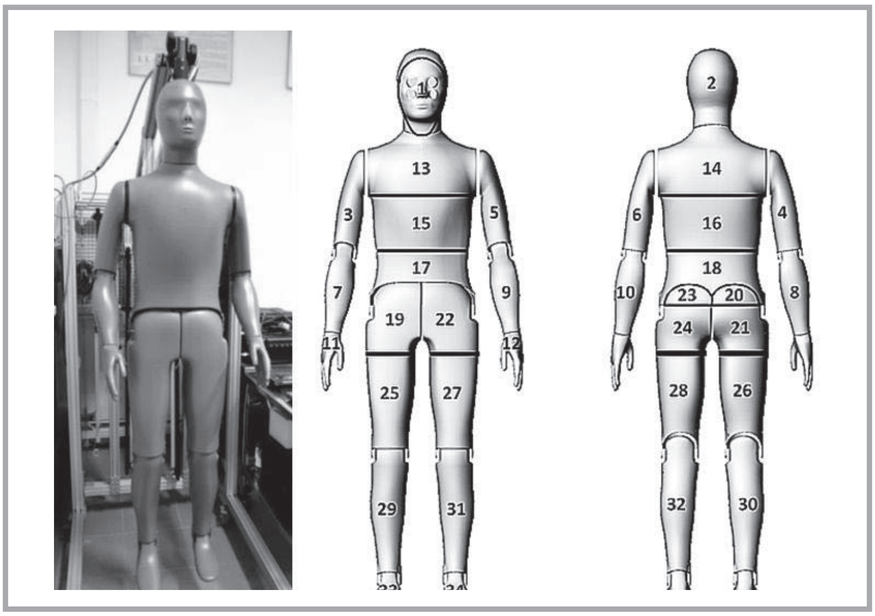

Figure 1. *Schematic view of the thermal manikin (Newton) divided into segments.*

Figure 2. *Sample of the firefighter personal protective clothing (EN_2).*

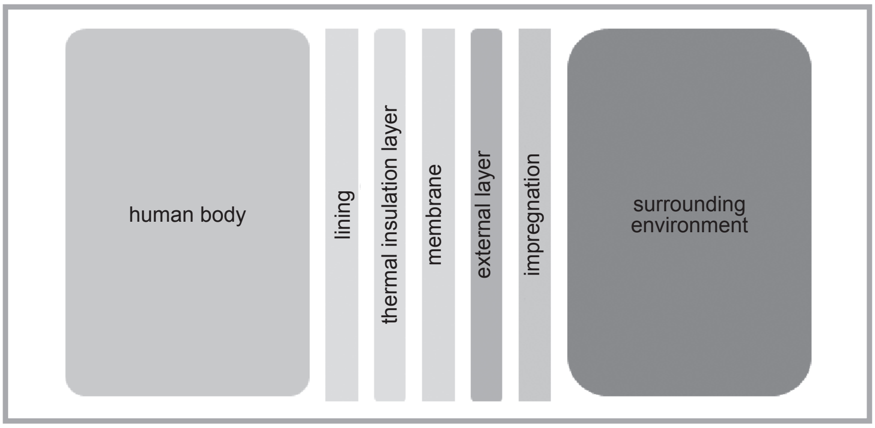

Figure 3. *Scheme of the multilayer structure of special clothing for firefighters.*

Clothing

Three sets of special clothing (FFPPC) intended for firefighting and similar actions, such as rescue and disasters, were used, two of which (EN_1 and EN_2) are currently used in Poland (***Figure 2***). The sets tested are in compliance with the EN 469 [3] standard (second level of protection (Xf-2, Xr-2, Y-2, Z-2)).

FFPPC has a multilayer construction [6, 11], a schematic diagram of which is shown in ***Figure 3*** [2, 3, 6, 10, 11].

As seen from the outside environment, the special clothing consists of:
- an external fabric layer;
- a membrane;
- a thermal insulation layer;
- lining.

The outer (external layer) is the first layer of protection, providing protection against flame, heat, chemicals and mechanical injuries. This layer is usually impregnated. The moisture barrier (a membrane) protects against water and other liquids, like chemicals and bloodborne pathogens. The thermal insulation layer protects the firefighter's body against environmental heat. The inner liner (lining) protects against direct contact of the human skin with the thermal barrier [11].

The clothes tested differed in terms of the materials used for each layer of the structure. A summary of materials used for the clothing ensembles tested is shown in ***Table 1***.

Individual layers of the firefighters' special clothing differed mainly in the percentage of each aramid isomer and the materials used in the lining layer.

Thermal parameters of FFPPC

Thermal insulation. Thermal insulation tests of the clothes selected were conducted in accordance with the EN ISO 15831:2004 [7] and EN 342 [8] standards. Thermal insulation is described by two units: m^2 °C/W or clo (1 clo equals 0.155 m^2 °C/W). The tests determined the total thermal insulation of the clothes ($R_{ct} = I_t$). During the tests, the thermal manikin was wearing special fabric skin (***Figure 2***), and its surface temperature was set at 34.0 °C.

Calculation of the thermal insulation of a clothing ensemble is based on two methods: the serial model and parallel model [7]. In the case of the serial model, the total thermal insulation is the sum of insulations calculated for particular segments [7]:

$$R_{ct} = I_t = \sum_{1}^{n} f_i \left[\frac{(t_{si} - t_a) \times a_i}{H_{ci}} \right]$$

where:

t_{si} – temperature on the surface of *i*-segment of manikin, °C;

t_a – air temperature in climatic chamber, °C;

H_{ci} – sensible heat loss from *i*-segment of manikin, W;

a_i – surface area of *i*-segment of manikin, m^2;

f_i – part of total surface area which contains *i*-segment of manikin.

In the case of the parallel model, thermal insulation is the insulation relating to the whole body of the manikin [7]:

$$R_{ct} = I_t = \frac{\left[\left(\sum f_i \times t_{si}\right) - t_a)\right] \times A}{\sum H_{ci}}$$

where:

A – total surface area of manikin, m^2.

According to EN ISO 15831 [7], the error permitted between measurements is 4%.

Insulation tests were carried out in an environmental chamber with the parameters set as follows: air temperature 12 °C, relative humidity 45% and air velocity 0.4 m/s. The thermal parameters in the climatic chamber were controlled by microclimate meters (***Table 2***).

Evaporative resistance. The evaporative resistance of the clothing ensemble (R_{et}) was tested with the thermal manikin wearing a special fabric skin (***Figure 2***). The test conditions complied with the ASTM F2370-10 standard [8]. There is no an European equivalent of this standard, which describes the measurement of evaporative resistance (R_{et}) on a thermal manikin. The manikin surface temperature for most segments was 34.0 °C and the sweat rate – 400 ml/h·m^2 (***Figure 4***).

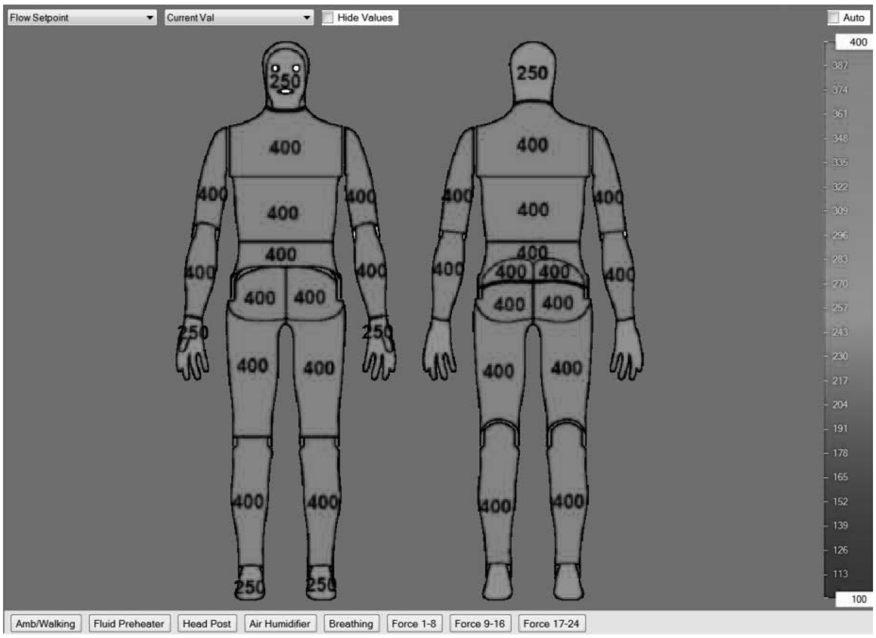

Figure 4. *Sweat rate values on each segment of the manikin.*

Table 1. *Materials used for the tested clothing ensembles.*

Layer	EN_1	EN_2	EN_3
External	64% meta-aramid, 35% para-aramid, 1% anti-static fibres	75% meta-aramid, 23% para-aramid, 2% anti-static fibres	94% meta-aramid, 5% para-aramid, 1% anti-static fibres
Membrane	65% para-aramid, 35% polyurethane	50% melamina 50% meta-aramid, coating 100% polyurethane	95% meta-aramid, 5% para-aramid
Thermal insulation	aramid, flame retardant fibres	65% meta-aramid 20% para-aramid, 15% polyethylene	100% para-aramid
Lining	50% aramid fibre, 50% viscose	100% cotton flame retardant	93% meta-aramid, 5% para-aramid, 2% P140 (carbon fibre)

Table 2. *Microclimate parameters in the climatic chamber during testing of the thermal insulation of the clothing ensembles.*

Clothing ensemble		t_a, °C	V_a, m/s	RH, %
EN_1	test_1	12.4±0.1	0.35±0.05	46±1
	test_2	12.4±0.1	0.35±0.05	48±1
EN_2	test_1	12.4±0.1	0.42±0.05	51±1
	test_2	12.4±0.1	0.42±0.05	51±1
EN_3	test_1	12.4±0.1	0.41±0.05	54±1
	test_2	12.4±0.1	0.41±0.05	56±1

All calculations were based on the heat loss method, defined as [9]:

$$R_{et\_heat,p} = \frac{p_{sk} - p_a}{\sum_{i=1}^{n} \left(\frac{A_i \times H_{ei}}{A} \right)}$$

where:

$R_{et\_heat,p}$ – total clothing evaporative resistance calculated by the heat loss method kPa · m^2/W;

A, A_i – total sweating surface area and segmental sweating surface area, respectively, m^2;

i – number of segments of the sweating thermal manikin (i = 1, 2,..., n);

p_{sk}, p_a – water vapour pressure on the whole fabric skin surface and in ambient air, respectively, kPa;

H_{ei} – segmental evaporative heat loss, W/m^2.

The water vapour pressures at the fabric skin surface and in the air temperature were calculated by Antoine's equation:

$$p_{sk} = \exp\left(18.956 - \frac{4030.18}{t_{sk} + 235} \right) \times RH_{sk}$$

$$p_a = \exp\left(18.956 - \frac{4030.18}{t_a + 235} \right) \times RH_a$$

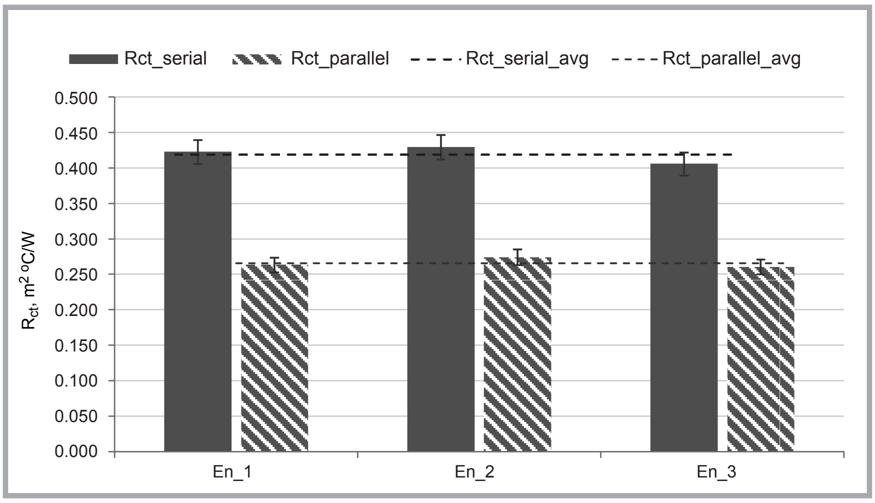

Figure 5. *Total thermal insulation R_{ct} obtained (with the permissible 4% measurement error).*

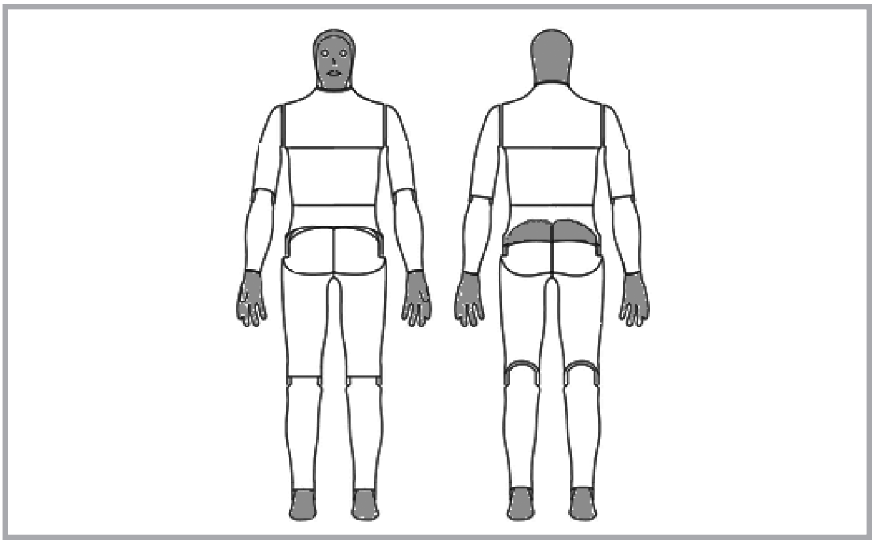

Figure 6. *Selected segments of the manikin with no direct influence of the clothing tested.*

Table 3. *Microclimate parameters in the climatic chamber during testing of the evaporative resistance of the clothing ensembles.*

Clothing ensemble		t_a, °C	V_a, m/s	RH, %
EN_1	test_1	12.3±0.1	0.38±0.05	69±1
	test_2	12.2±0.1	0.39±0.05	68±1
EN_2	test_1	12.2±0.1	0.38±0.05	41±1
	test_2	12.2±0.1	0.39±0.05	64±1
EN_3	test_1	18.2±0.1	0.43±0.05	50±1
	test_2	18.2±0.1	0.38±0.05	62±1

Table 4. *Absolute percentage difference in the local thermal insulation R_{cti} between the ensembles tested.*

Segments\ensemble	(EN_1 – EN_2)	(EN_1 – EN_3)	(EN_2 – EN_3)
Upper Chest	12%	33%	19%
Shoulders	0%	59%	58%
Mid Back	2%	18%	19%
Waist	34%	19%	22%
Lower Back	12%	21%	8%
R Up Thigh Fr	31%	34%	5%
R Up Thigh Bk	50%	39%	7%
L Up Thigh Fr	16%	27%	13%
L Up Thigh Bk	67%	34%	20%

where:

t_{sk}, t_a – temperatures at the wet fabric skin surface and in ambient air, respectively, °C;

RH_{sk}, RH_a – relative humidity at the wet fabric skin surface and in ambient air, respectively, % (assuming that RH_{sk} on the saturated wet fabric skin surface was 100%).

According to ASTM F2370-10 [9], the error permitted between measurements is 10%.

As required, they corresponded to ‘non-isothermal conditions’ under the same conditions as for dry heat exchange. The thermal parameters in the climatic chamber were controlled by microclimate meters (***Table 3***).

Results

Results from the thermal insulation and evaporative resistance tests performed on selected clothing are presented below.

Total thermal insulation

A summary of the total thermal insulation (calculated by two mathematical methods and with the permissible 4% measurement error) is shown in ***Figure 5***.

The mean value of the total thermal insulation of the clothing ensembles tested is 0.419 ± 0.012 m^2 °C/W. The R_{ct} resulting in both the serial and parallel calculations are within the 4% permissible measurement error (***Figure 5***).

In order to find out whether the use of other materials affected the thermal resistance, despite the approximate final R_{ct} value, the local thermal insulation (R_{cti}) was calculated for selected segments of the manikin where the tested clothing had a direct influence (***Figure 6***).

For most segments no significant differences in the local thermal insulation were noted (***Figure*** *7*).

Differences in the local thermal insulation of the clothing ensembles were recorded mainly on the trunk of the manikin (***Figure 8***).

The percentage difference measured by the local R_{cti} was calculated on selected segments of the manikin for 3 sets of clothing. A difference of >4% is shown in ***Table 4***.

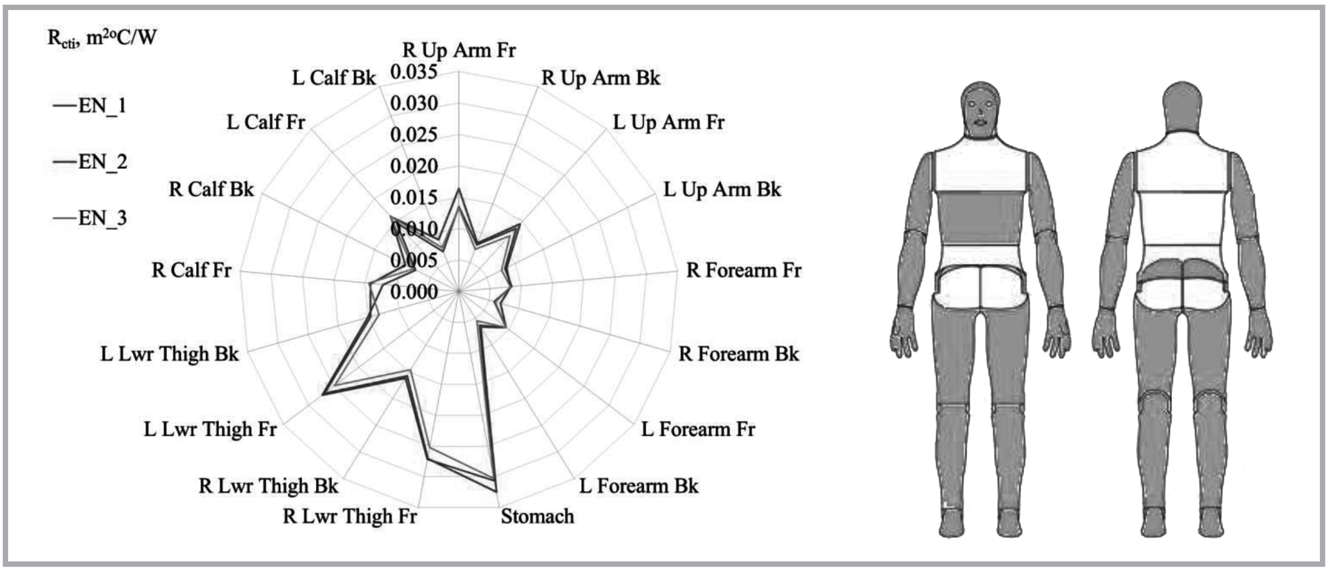

Figure 7. Local thermal insulation and segments obtained where no significant differences were noted (blue colour – selected segments with no direct influence of the clothing tested; green colour – segments with no significant differences; white colour – segments with significant differences).

Out of the segments selected, only the shoulders and middle back showed no differences between EN_1 and EN_2.

The reason for the differences may lie in the material used and lack of precision in fitting of the clothing to the manikin. The biggest differences, which most probably resulted from poorly fitting clothing, were found in the following segments: the upper thigh (front, back, right, left), waist, lower back and middle back. The size of clothes were fitted to the manikin's dimensions. Theoretically, all clothes should have had the same size, but in practice there were differences.

Evaporative resistance

Evaporative resistance tests of the clothing (R_{et}) were carried out for an assumed intensity of sweating equal to 400 ml/h · m^2 (***Figure 4***). A summary of the evaporative resistance of the tests is shown in ***Figure 9***.

R_{et} values for the individual sets of special clothing were similar (***Figure 9***). The maximum difference between the results was <10%, i.e. below the permissible error between evaporative resistance tests [8] (***Figure 9***).

The membrane used (EN_1: 65% para-aramid, 35% polyurethane; EN_2: 50% melamine 50% meta-aramid, 100% polyurethane coating, EN_3: 95% meta-aramid, 5% para-aramid; see ***Table 1***) and other layers of clothing did not significantly affect the evaporative resistance.

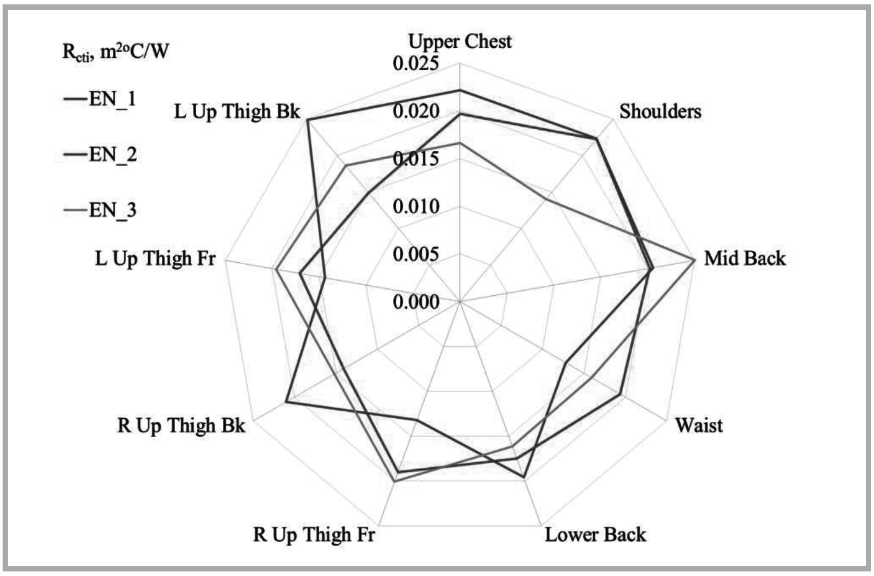

Figure 8. *Local thermal insulation obtained on the segments where significant differences were noted.*

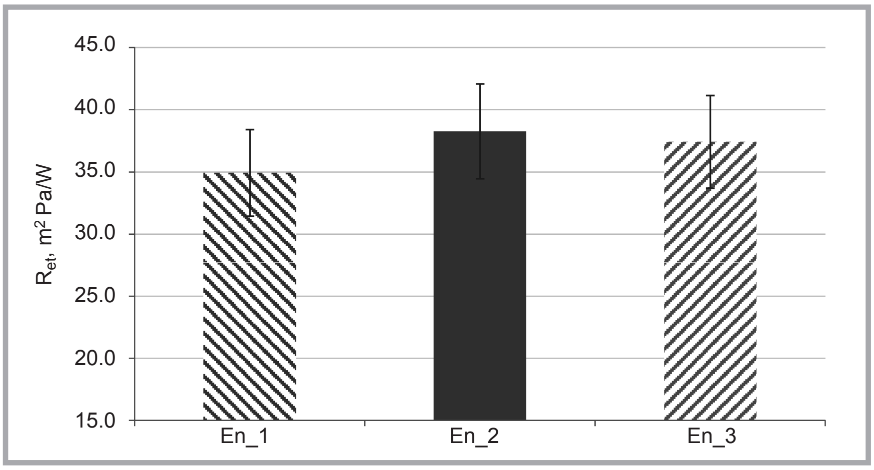

Figure 9. *Evaporative resistance R_{et} values obtained together with the 10% error of measurement permitted.*

Disscusion and summary

The thermal parameters of specialised firefighters' clothing, such as the thermal insulation and evaporative resistance, were measured. Based on the analysis and calculations of the test results, it was shown that special clothing for firefighters provides a barrier to the heat exchange between the user and the surrounding environment.

According to the normative requirements, there are no limit values for the thermal insulation of such a type of clothing. This is due to the fact that clothing intended for firefighters should be used regardless of weather conditions. The mean value of the clothing's total thermal insulation obtained from the tests is 0.419 ± 0.012 m^2 °C/W. The best-fitting clothes were found to be on the upper chest and shoulders of the manikin. The biggest differences, which most probably resulted from the non-adherent clothing, were found for the following segments: the upper thigh, waist, lower back and middle back. The materials used for the EN_1 and EN_2 ensembles did not affect the local value of thermal insulation R_{cti}. The materials used for EN_3 provided a lower level of protection than fabrics used in EN_1 and EN_2. The local values of thermal insulation were lower than in the other ensembles tested.

The similar results of thermal insulation were obtained by Zhu et al. [12]. The thermal insulation of a material structure consisting of aramid (outer shell), a PTFEE (polytetrafluoroethylene) membrane (moisture barrier) and para-aramid fibre (thermal barrier) was equal to 0.404 m^2 °C/W. According to Zhu et al. [12], the effect of the thermal barrier material is stronger than that of the outer shell material.

It should be noted that this value applies only to firefighters' clothing. Under real conditions, appropriate underwear is put under the outer layer in addition to other equipment, such as gloves, boots, a balaclava and a helmet, which increase the total thermal insulation of the entire set for firefighting operations. On the one hand, FFPPC should provide complete protection from heat exposure (then a high value of thermal insulation is indicated). On the other hand, the use of highly insulating clothing hampers the exchange of heat produced by the human (metabolic heat) to the environment, proving that it is very difficult to ensure thermal comfort and protection performance at the same time [11].

Not only the heat transfer affects firefighters' sense of comfort but also moisture transfer, the latter being a very important process, associated with the evaporation, condensation, absorption and desorption of moisture [11]. If the materials used are not appropriately selected, the sweat will condensate on the skin and accumulate on the inner layer of clothing, thus leading to a wetness sensation and increase in the wearer's discomfort. The parameter describing moisture transfer is the evaporative resistance (R_{et}) [9]. According to the EN 469 standard [3], the critical value for R_{et} is 0.030 m^2kPa/W, below which the clothing meets the requirements of the second level of protection. The mean value of the evaporative resistance of the clothing tested was 0.037 ± 0.002 m^2kPa/W, exceeding the critical value. It needs to be pointed out that according to EN 469 [3], R_{et} should be measured with a sweating skin model (a hot plate), but the test was performed on one piece of the multilayer fabric. In the present research, R_{et} was measured on a full-size thermal manikin, and the manikin's tests were more similar to real conditions of use. The results could be different if various measuring equipment were used. It should also be pointed out that a single sample of fabric is arranged differently on the measuring surface than on the entire set of clothing.

There was no difference in R_{et} between the clothes tested. The membranes used for testing purposes and other layers of clothing did not significantly affect the evaporative resistance value. Perhaps the use of a higher class membrane would show a significant difference in the R_{et} value.

For a material structure consisting of aramid (outer shell), para-aramid fibre (thermal barrier) and a PTFEE membrane (moisture barrier), the evaporative resistance R_{et} was equal to 0.048 m^2kPa/W [12]. The higher class membrane changed the value of R_{et}.

In order to further examine the impact of the materials used on the thermal parameters of the clothing, it is necessary to analyse the impact of individual layers. Furthermore, it would also seem helpful to perform separate analyses of individual clothing layers to find out which part of the structure should be improved.

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